A PROPOSED FEDERAL STANDARD FOR NARROWBAND DIGITAL LAND MOBILE RADIO

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ABSTRACT

Steadily increasing demands on available spectrum for VHF and UHF Land Mobile Radio (LMR) usage make it necessary to plan for future systems which can operate with channel spacing narrower than the currently designated 25 kHz spacing. GTE Government Systems is supporting the federal government in developing a new Federal Standard (Fed Std 1024) for a future generation of narrowband digital land mobile radios. The standard will define interoperable digitized voice and digital data modes operating at 8000 bits/s with 12.5 kHz or narrower channel spacings at frequencies above 30 MHz. This paper describes the technical characteristics and features of the proposed new standard.

1. INTRODUCTION

Since its first use in the early 1920s, Land Mobile Radio has expanded and evolved steadily, and today it is estimated that there are several tens of millions of LMR users in the U. S. alone. LMR systems provide a wide range of mobile communications capability, from small single-channel nets to large networks employing trunking systems and repeaters to cover large geographical areas [1]. Users of LMR systems include a wide variety of industrial, land transportation, and public safety organizations, as well as many sectors of the federal government. It is estimated currently that there are over one million federal government users of LMR equipment. All of the military services use LMR extensively for military base security. In addition, LMR is used by many government officials needing full-time access to communications, and is relied upon heavily by federal law enforcement agencies. Various VHF and UHF bands are designated for LMR communications by commercial, public safety and federal government users. (It should be noted that, by standard usage in the industry, the designation Land Mobile Radio excludes cellular radio telephone as well as military combat radio systems, which also operate in the VHF and UHF bands.) The work described in this paper has concentrated on the needs of the federal government for LMR communications.

The steady expansion of federal government use of LMR has made interoperability an increasingly important issue. Over many years, there were no government standards for LMR modulation techniques, and so LMR products from different manufacturers could not be guaranteed to interoperate. As the LMR industry has moved into digital technology, the interoperability issue has become more acute. The steadily increasing use of LMR by federal agencies has led to the development of a series of federal standards as a means of insuring interoperability of the government's LMR systems.

In September 1989, the National Communications System (NCS) Office of Technology and Standards approved Fed Std 1023, which defines interoperability requirements for one category of encrypted 12 kbit/s CVSD voice digitizers operating with 25 kHz-channel FM radios at frequencies above 30 MHz [2]. The government regards Fed Std 1023 as an interim standard, based on LMR technology then-current when the standard was being developed.

While work on Fed Std 1023 was in progress, the government began planning for the next-generation digital LMR standard. An important issue in the development of future standards is the steadily increasing demand for limited spectrum. One critical aspect of this is the need for U. S. Armed Forces to operate LMR systems overseas, where various governmental spectrum management agencies are mandating narrower channel spacings and signal bandwidths within the next few years.

In June 1988, GTE Government Systems began providing technical support to DoD in their development of a future digital LMR standard, to be designated as Fed Std 1024. In particular, GTE was asked to develop technical data and make recommendations to the government with respect to data rate, modulation, channel coding, and synchronization techniques for reliable digital LMR operation at VHF and UHF frequencies.

In January 1989, the NCS Technical Standards office published a notice in the Federal Register announcing its plan to draft a new federal standard for "Narrowband Digital Land Mobile Radio," Fed Std 1024 [3]. The principal objectives for Fed Std 1024 include: (1) a modulation technique permitting operation with 12.5 kHz or (as a goal) 6.25 kHz channel spacing; (2) inclusion of the government standard 4800 bit/s voice digitization technique known as Code Excited Linear Predictive (CELP) coding; and (3) reliable initial and late-entry synchronization in the fading/multipath environment typical of VHF/UHF radio channels.

2. DATA RATE AND TRANSMISSION MODES

A key ingredient in the definition of a narrowband LMR standard is establishing a transmitted data rate which is sufficiently high to accommodate the source information (digitized voice bits or other digital data), channel coding, and various types of necessary overhead bits, while allowing the on-air waveform to operate with narrow channel spacing, *i. e.*, 12.5 kHz or even 6.25 kHz. After extensive study of all the requirements for data to be transmitted, a composite data rate of 8 kbits/s was selected as the data rate for all transmission modes. This data rate was found to provide sufficient bits for all the user data, channel coding and overhead, while, with an appropriate modulation technique (Section 4), allowing channel spacings as small as 6.25 kHz throughout the VHF and UHF bands.

The recommended design for Fed Std 1024 provides for interoperability in three principal transmission modes: a digitized voice mode and two data modes. In addition, the transmission format is designed to allow implementation of other interoperable modes, such as network control modes. The transmission rate in any mode is

8000 bits/s, and in each mode 10 per cent of the data rate, 800 bits/s, is devoted to overhead bits (does not apply to Header and End-of-Message bits).

In the digitized voice mode, 4800 bits/s are devoted to transmitting voice bits, and 2400 bits/s to channel coding. Fed Std 1024 will specify that the voice transmission be digitized using the government standard Code Excited Linear Predictive (CELP) coding algorithm. The details of the government CELP algorithm will be specified by a separate federal standard, Fed Std 1016, which is still under review at this writing [4]. A high-level description of the government standard voice coder is available in a 1989 ICASSP paper [5]. The error-control for the voice bits is provided by the (24,12) Golay code, which is used to protect the most sensitive half of the voice bits in each CELP frame, so that 2400 bits/s of parity checks are added to the 4800 bit/s voice bit stream. This error-control technique, as used with CELP coding for LMR application, was investigated in detail by the government and has been described in a 1990 ICASSP paper [6]. It is estimated that by decoding the Golay code with soft-decision decoding, acceptable CELP decoder voice quality can be achieved on channels having bit error rates as high as 10 per cent.

Two different data modes will be specified in Fed Std 1024. One, named the Coded Data Mode, will provide a source data rate of 2400 bits/s, coded with a rate-1/3 Reed Solomon (RS) code, which will add 4800 bits/s of parity checks to the transmission. The standard will specify interleaving of RS code blocks as a means of combating error bursts likely to occur on VHF and UHF channels. RS coding with interleaving has been shown to be a highly effective means of error-control on fading/multipath channels [7]. In a second data mode, designated the Uncoded Data Mode, a 7200 bit/s data rate will be available to the user. The user may use this data interface without link coding, or use a lower source data rate with user-defined coding to bring the total data rate to 7200 bits/s (*e. g.*, 1200 bit/s data with rate-1/6 coding).

3. TRANSMISSION FORMAT

Based on the requirements to transmit voice and data, use a channel spacing of 12.5 kHz (goal of 6.25 kHz), and to provide for synchronization performance equal to or better than today's secure voice radio systems (KY-57, -58), a recommendation has been developed by GTE for Fed Std 1024 which will meet or exceed these requirements.

The basic "building block" for the transmission is the frame length (30 ms) for the government standard CELP voice coding algorithm [4]. Thus the transmission is composed of 30 ms frames (240 bits/frame), which we have organized into superframes. There are both secure and non-secure modes. For the secure modes, there are 14 frames per superframe in the transmission format, for a superframe length of 420 ms. For the non-secure modes, there are 8 frames per superframe in the transmission format, for a superframe length of 240 ms. Table 1 summarizes the breakout of bits per superframe and bits per second for both the secure and non-secure voice modes.

The overall transmission format, shown in Figure 1, consists of the Header field, the Information field, and the End-of-Message (EOM). The bits in the information field are interleaved to combat the effects of the fading channel. In the non-secure modes, the data bits are scrambled in accordance with a scrambler polynomial to prevent long series of "1s" or "0s".

The function of the clock recovery is to establish bit timing. The framing and synchronization field contains the framing sequence, mode selection, Message Indicator (crypto sync vector), and some unassigned bits (for future growth). The superframes contain the user-supplied voice or data, voice or data parity bits, and the overhead, consisting of Framing (providing for "late entry" synchronization), Mode Control, Message Indicator, System Control, and the parity bits for each of these. The EOM is a unique 240-bit sequence that indicates end of transmission. The function of the Header is to provide rapid initial synchronization and to set the receiver into the correct mode to correctly interpret the type of information to follow in the next superframe.

Table 1. Superframe Bit Counts (Voice Modes) for Fed Std 1024

	SECURE VOICE (420-ms Superframe)		NON-SECURE VOICE (240-ms Superframe)	
	Bits/SF	Bits/s	Bits/SF	Bits/s
Framing	48	114.29	48	200.00
Mode Control	24	57.14	24	100.00
Crypto Sync	144	342.86	0	0.00
Sys Control	120	285.71	120	500.00
Voice	2016	4800.00	1152	4800.00
Voice EDAC	1008	2400.00	576	2400.00
Totals:	3360	8000.00	1920	8000.00

4. MODULATION TECHNIQUE

The critical element in designing the standard was to select a modulation technique which could transmit the 8000 bits/s with a significant reduction in channel spacing relative to current LMR frequency assignments. In our work, we have assumed the goal of 6.25 kHz channel spacing as an implicit requirement. Therefore the specific technical objective of our modulation study has been to find a digital modulation technique capable of transmitting 8000 bits/s with a channel spacing as narrow as 6.25 kHz. We note that implies a bandwidth utilization of up to 1.28 bits/s per Hz.

We now describe the modulation candidates which were examined and outline briefly the performance parameters which were key to the selection of a modulation technique [8].

4.1 Candidate Modulation Types

The modulations examined in this study were:

(1) Binary FM as used in the SINCGARS combat net radio
(2) Generalized Tamed FM (GTFM)
(3) 4-ary Frequency-Shift Keying (FSK)
(4) Quarternary Differential Phase-Shift Keying (QDPSK)
(5) $\pi/4$-Shift QPSK

The SINCGARS binary FM modulation served as a baseline waveform for our modulation study. The QDPSK and GTFM schemes were originally chosen as candidate modulations at an early point in our study. The $\pi/4$-shift QPSK is the modulation which has been selected by the EIA for the future digital cellular system [9]. The 4-ary FSK modulation is a recommendation from one of the LMR equipment manufacturers for adoption in Fed Std 1024.

These modulations fall into two basic categories. The GTFM and 4-ary FSK are constant-envelope modulations, which are well-suited for nonlinear, *e. g.* Class-C, amplification. (GTFM is pre-filtered binary FM modulation.) They can be viewed as extensions of the binary FM modulations used in present-day digital LMR equipment. The QDPSK and $\pi/4$-Shift QPSK waveforms are 4-ary phase-shift waveforms that are filtered to form linear (*i.e.*, non-constant-envelope) waveforms; they are best suited for linear amplification [10]. It can be shown that the QDPSK and the $\pi/4$-shift QPSK waveforms are similar to each other, and the GTFM and 4-ary FSK waveforms are in turn similar to each other. In the version of QDPSK we have evaluated here, Square-Root Raised Cosine filtering is done both at the transmitter and receiver; later in the paper we refer to this

as QDPSK-RC modulation. Also, the form of 4-ary FSK we evaluated used Square-Root Raised Cosine filtering at both transmitter and receiver.

Linear modulation techniques are being considered because they can provide significantly greater spectral utilization (more bits/s per Hz) than FM waveforms. As an example, the future digital cellular system, which will use $\pi/4$-shift QPSK, is being specified to transmit at least 40 kbits/s in a 30 kHz channel, for a spectrum utilization of at least 1.33 bits/s per Hz [9].

4.2 BER Performance and ACIPR

The basic performance characteristics that we examined for the candidate modulations are the bit-error rate (BER) in both additive white Gaussian noise (AWGN) and Rayleigh fading; and the adjacent channel interference protection ratio (ACIPR).

In general, the BER performance of any modulation scheme is affected by the channel characteristics, transmit and receive filtering, the type of transmitter power amplification, and adjacent channel interference (ACI). The BER performance predicted for any given modulation type translates directly into communication range for a given amount of radiated signal power.

The level of achievable ACIPR is a critical issue in the selection of a modulation technique for LMR. Achievable ACIPR depends upon the transmitted signal spectrum and the bandwidths and shape factors of the filters in the receiving equipment. We note that the ACIPR is a function of the receive operating point. For our study, we determined ACIPR for the level of E_b/N_0 such that the probability of bit error equaled 10^{-2}. ACIPR is the ratio of ACI-to-desired signal that degrades performance 3 dB from the operating point. We assumed the desired level of ACIPR to be 50 dB or better.

Figure 2 shows the BER performance of binary FM (SINCGARS), GTFM, 4-ary FSK, and QDPSK-RC in AWGN. We have not shown a BER curve for the $\pi/4$-Shift QDPSK modulation. However, for reception in AWGN with differentially coherent demodulation, the BER performance is exactly the same as that for QDPSK-RC. Noncoherent binary FSK with orthogonal tone spacing is shown for comparison with theory. Clearly, QDPSK-RC has the best BER performance of all the schemes. The QDPSK-RC scheme is about 4 dB better than GTFM and about 1.5 dB better than SINCGARS at $P_b = 10^{-2}$. It can be shown that by using a Viterbi algorithm at the receiver, the BER performance of GTFM in AWGN can be improved by about 2 dB [11]. For the Viterbi algorithm case, the GTFM curve would be only about 0.5 dB poorer than SINCGARS at high E_b/N_0. The 4-ary FSK curve is similar to SINCGARS, showing almost 2.5 dB advantage relative to GTFM and therefore only about 1 dB disadvantage relative to the best-performing modulation, QDPSK-RC. If the GTFM waveform is implemented with a Viterbi algorithm, the performance of all the constant-envelope schemes would come nearly together, so that we can say roughly that linear modulation retains a BER performance advantage of about a 1 dB relative to the constant-envelope modulations examined here.

We note that the simulations for Figure 2 used filter bandwidths chosen to reduce ACI to the greatest extent possible consistent with minimal sacrifice in BER performance. As a practical matter, filter bandwidths in actual designs may be somewhat wider than those indicated in the figure, but this will have almost no influence on the relative placement of the various BER curves. (Choices of filter bandwidths and shape factors have their greatest effect on achievable ACIPR.)

Figure 3 shows the BER performance of the same waveforms in Rayleigh fading. Only curves for 100 Hz RMS Doppler spread are shown, representing the most rapid fading condition likely to be encountered on LMR channels. We observe that at low E_b/N_0 (i.e., below about 20 dB), the QDPSK-RC scheme has better BER performance than SINCGARS, GTFM, and 4-ary FSK. Above E_b/N_0 = 20 dB, the SINCGARS modulation performs best , while the other schemes begin to show irreducible error rates. An irreducible error rate for QDPSK-RC approximately equal to 4×10^{-3} occurs for this Doppler spread of 100 Hz. From the simulation data , the irreducible error rate for GTFM at this same Doppler spread occurs at a somewhat lower, but unknown, BER. For 4-ary FSK an irreducible error rate slightly below that of QDPSK-RC appears to occur for a 100 Hz RMS Doppler spread. For the SINCGARS modulation, the irreducible error rate is much lower and occurs at a much higher E_b/N_0.

It should be noted that the 100 Hz RMS Doppler spread represents an extreme case (800 MHz carrier and 60 mph vehicle speed). At lower LMR carrier frequencies and more typical speeds, irreducible error rates will not be a problem. However it is worth noting that the (constant-envelope) waveforms detected with a frequency discriminator will generally exhibit lower irreducible error rates than the linear modulations, which are detected by coherent or differentially coherent phase demodulation.

It needs to emphasized that the BER performance comparisons shown above are based on received signal power (or, equivalently, radiated signal power) and therefore do not reflect the power efficiency of the transmitter. On this basis of comparison, the linear and constant-envelope modulations can be brought to within about 1 dB of each other. However, the overall power efficiency for the two classes of modulation can be very different; depending in large part on the efficiency of the transmit power amplifier.

The level of achievable ACIPR is a critical issue in the selection of a modulation technique for Fed Std 1024, since ACIPR translates directly into restrictions on channel assignments and, therefore, on overall spectrum utilization. An important result of this study has been the observation that phase-shift-keyed waveforms can be "filtered heavily" without serious degradation of their BER performance. The resulting signal spectra have skirts which roll off sharply compared with constant-envelope waveforms, and this sharper rolloff allows correspondingly closer spacing of adjacent channels.

Figure 4 shows spectra of GTFM, 4-ary FSK, QDPSK-RC and binary FSK (SINCGARS) modulation. (We must note that the spectral plots are not normalized for equal power; they are presented only for comparison of roll-off characteristics.) From these spectra it is easy to understand why QDPSK-RC, when linearly amplified, has much better ACI protection with 6.25 kHz channel spacing than any of the other schemes. Quaternary Differential Phase-Shift Keying with Raised Cosine filtering (QDPSK-RC) provides the best ACI protection of all the modulations we have examined. However, it is necessary to use a linear amplifier in order to obtain desired levels of ACIPR.

For 6.25 kHz channel spacing, our results show that the constant-envelope modulations cannot provide desired levels of ACIPR, and there is no alternative but to use a linear modulation.

For 12.5 KHz channel spacing, QDPSK-RC with linear amplification still provides the best ACIPR, and can meet the desired ACIPR performance ($\geq$ 50 dB). For this channel spacing, the ACIPR capabilities for GTFM and 4-ary FSK are significantly improved over their ACIPR capabilities in 6.25 kHz channel spacing, and they can probably be made to meet the desired ACIPR performance. Thus if LMR channels are narrowed only to 12.5 kHz, both linear and constant-envelope modulations are candidates. At some channel spacing intermediate between 12.5 and 6.25 kHz (we estimate around 8 to 10 kHz) there is a "crossover" point at which constant-envelope modulations must be dropped out of consideration on the basis of unsatisfactory levels of achievable ACIPR.

4.3 Modulation Selection

In summary, our modulation study shows that there is potential for accommodating 6.25 kHz LMR channel spacing with the 8000 bits/s Fed Std 1024 baseline by using a filtered linear modulation. Of the two candidate linear modulations, the $\pi/4$-Shift QPSK waveform has an advantage in power efficiency (due to lower peak-to-average power ratio) and is preferred for this reason. Furthermore, since this modulation has now been adopted for the future digital cellular system, the development of Fed Std 1024 radio equipment can benefit greatly from technological advancements that will surely be spurred on by the rapidly expanding market for cellular service. (It can be expected that demand will grow for small, lightweight handheld digital cellular phones, and the industry will have to address the power efficiency problem that comes with use of a linear modulation.) The adoption of a common modulation technique for digital cellular and digital Land Mobile Radio will also provide economy of scale through an enlarged manufacturing base of components for both types of products.

5. CONCLUSION

We have described a recommended standard for next-generation digital land mobile radio systems. The recommended.standard will provide both digitized voice modes and data modes. The voice modes will incorporate the government standard 4800 bit/s CELP voice coding algorithm. Both voice and data modes will utilize error-control coding with interleaving to combat error bursts typical of digital LMR communication channels. The baseband transmission format is designed with a superframe structure which will provide for reliable late-entry synchronization. The recommended standard includes a spectrally efficient modulation which will allow reducing LMR channel spacing from 25 kHz to 12.5 or 6.25 kHz.

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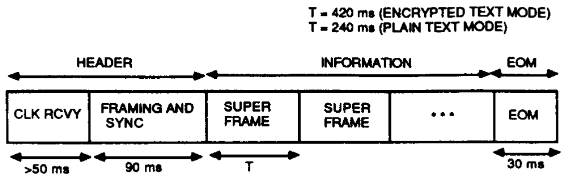

Figure 1. Baseband Transmission Format in Fed Std 1024

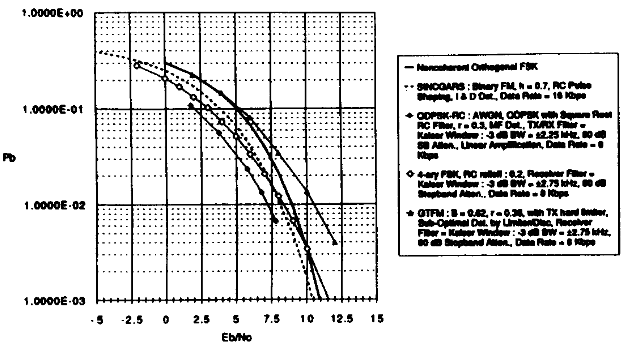

Figure 2. Simulated BER Performance in AWGN for SINCGARS, QDPSK-RC, GTFM, and 4-ary FSK

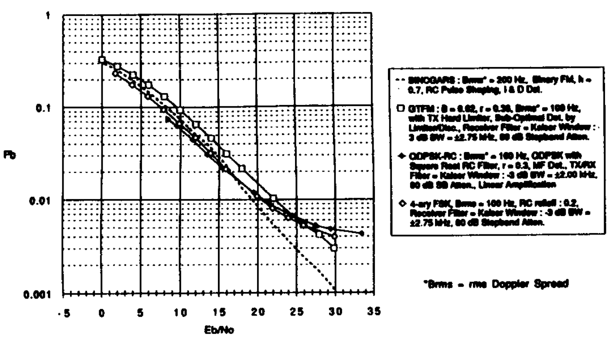

Figure 3. BER Performance in Rayleigh Fading for SINCGARS, QDPSK-RC, GTFM, and 4-ary FSK

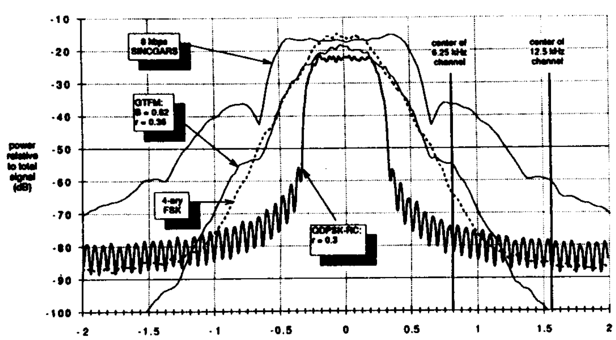

Figure 4. Power Spectral Densities of the Modulation Schemes